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TOR STUBB

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THE MEASUREMENT OF THE HALL EFFECT WITH THE AID OF MICROWAVES IN GERMANIUM SPECIMENS CHANGING FROM N-TYPE TO P- TYPE WITH CHANGING TEMPERATURE

by

TOR STUBB

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Physics Including Nucleonics Series Ph 11

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CONTENTS

There are few experimental methods elucidating the properties of a semiconductor material as fully as measurements of the Hall effect. Such measurements are usually carried out with direct current, but recently various high-frequency measuring methods have been treated theoretically as well as experimentally [1-12] . Hambleton & Gärtner [10] have shown that no difference can be demonstrated between D.C. measurements and microwave measurement up to 24 GHz, whereas an essential departure from the D.C. measurements can be discovered on 70 GHz, [12] .

In all high-frequency transport phenomena, the free carriers are out of phase with the superimposed high-frequency field, owing to the inertia of the carriers. No exact solution of this problem has been given, but one may approximately write for the Hall mobility:

$$\mu_H = \frac{q}{m(\omega_e + j\omega)} \qquad (1)$$

where

- q the electron charge
- m the effective mass of the carriers
- ω_e the collision frequency of the carriers
- ω the angular frequency of the high-frequency electromagnetic

The present work is a study of the Hall effect with the aid of microwaves in the X-band. Measurements were carried out by two different methods. The first method is based on the principle worked out by Nishina & Spry [9] . It is well applicable to measurements at constant temperature and with varying magnetic field but the resonator has to be tuned after any change of temperature. Large errors are thereby incurred, which are difficult to account for later. The measuring

accuracy with this method also decreases rather strongly, as there is a leakage effect dependent on the magnetic field even when the resonator is empty. The final measuring equipment was a modification of Hambleton and Gärtner's[10] equipment.

MEASURING PROCEDURE AND MEASUREMENTS

The system used for the measurements contains a crystal holder as shown in Fig. 1a. It consists of two waveguide sections whose axes are perpendicular and whose common wall has been replaced by the semiconductor crystal. The thickness of the crystal was 1 mm in our measurements. The electric field in the input waveguide produces a current in the sample in the vertical direction. The D.C. magnetic field applied perpendicular to the face of the crystal generates a microwave Hall voltage in a horizontal direction, which couples to the output waveguide. A simple analysis indicates that Hall mobility is related to the microwave powers in the applied and observed fields at the faces of the crystal in the following manner [12]:

$$\mu_H = \frac{I}{H} \left[\frac{P_{out}}{P_{in}} \right]^{1/2} \qquad (2)$$

where

- H the magnitude of the applied magnetic field
- P_{in} the power in the electric field at the input face of the crystal
- P_{out} the power in the electric field at the output face of the crystal.

Equation (2) is only valid for strong magnetic fields.

In order to achieve the best possible tuning of the system, the cryostat has been designed so that the tuning screws are located outside the cryostat itself. With such a design, the waveguide has to consist of German silver, as well as the cryostat proper. The latter has been made with double walls and the outer space has been evacuated. The entire microwave system was insulated from the magnet by means of a polystyrene sheet.

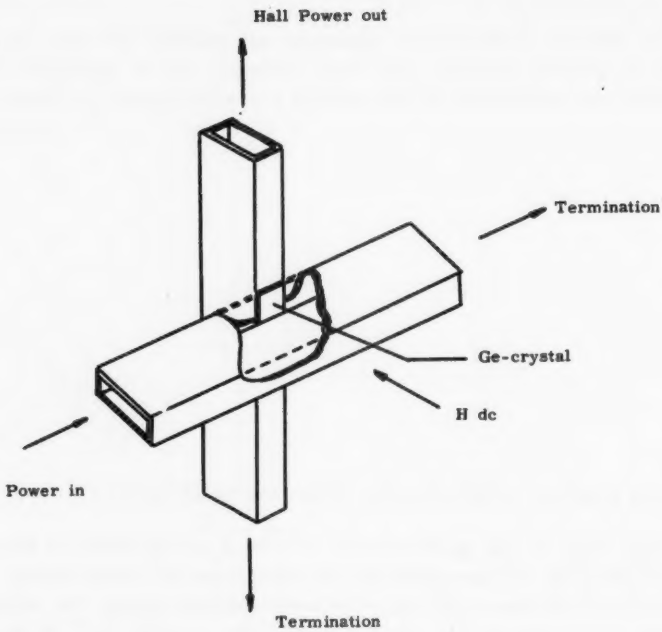

Fig 1 a.

The sample under measurement could be cooled down to 100°K in this device with the aid of liquefied air and by continuous evacuation of the system. It is particularly essential that the sample is in high vacuum or in a rare gas atmosphere so that the surface potential of the crystal is positively definable and its surfaces are not affected by moisture. The temperatures were measured with the aid of an STE 100 nickel resistance.

The entire microwave bridge is inserted in a microwave circuit similarly as was done by Hambleton & Gärtner [10], except that an extra attenuation shown in Fig. 1b was used. Moreover, the standing wave ratio was measured in both branches for different magnetic fields. An HP 620A signal generator was used. The frequency meter was of resonator type, manufactured by Sivers under the type designation SL 5205, while the standing wave indicator was type SL 5141/1. The amplifier was Kintel 203, with a Varian recorder as ultimate indicator. The attenuator was of the HP 885A type.

On very high frequencies variations can be shown to occur in the measurements, obviously resulting from tuning difficulties [12]. Similar differences were found in the present measurements, but they were entirely attributable to the positioning of the crystal. The crystal has to be placed symmetrically with respect to both waveguides, and it has to be framed with silver emulsion so that no leakage occurs along the edges.

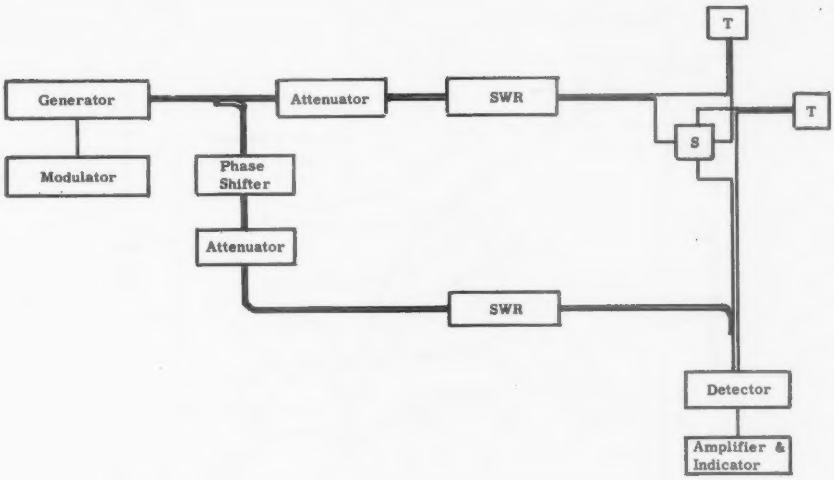

Fig. 1 b.

The equipment in its entirety was constructed for the purpose of Hall effect measurements having bearing on a complex of problems concerning the semiconductor properties of boron. As a check of the apparatus, measurements were made with germanium, which revealed on absorption in the Hall constant at 240 - 250^{o} K.

As the crystals were primarily intenden to be used for a check of the apparatus, their impurities were not known beforehand. However, it could be shown by quantitative spectral investigation that Al as well as Cu occur in the samples Furthemoore, the orientation of the crystals, the occurrence of dislocations and the etch-pitch distribution were investigated because absorption may occur on account of dislocations.

Measurement of the resistivity as a function of temperature by D.C. revealed a jump at the point where absorption occurred, Figs. 2, b and 3, b.

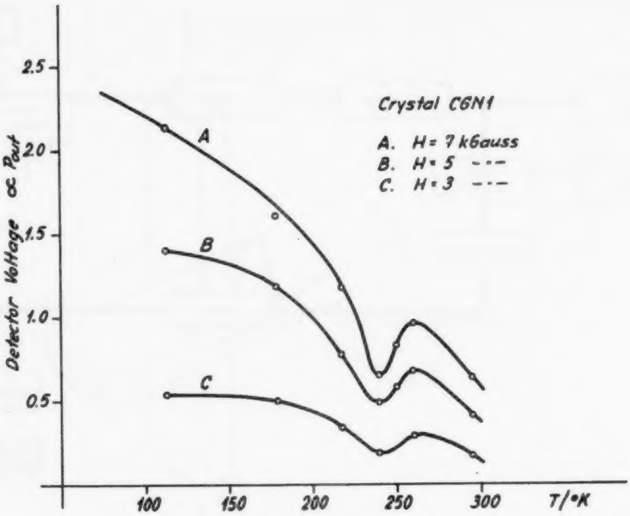
Crystal CGN1
A. H = 7 kGauss
B. H = 5 ---
C. H = 3 ---
A
B
C
Detector Voltage ∝ Pout
2.5
2.0
1.5
1.0
0.5
100
150
200
250
300
T/°K

Fig. 2 a.

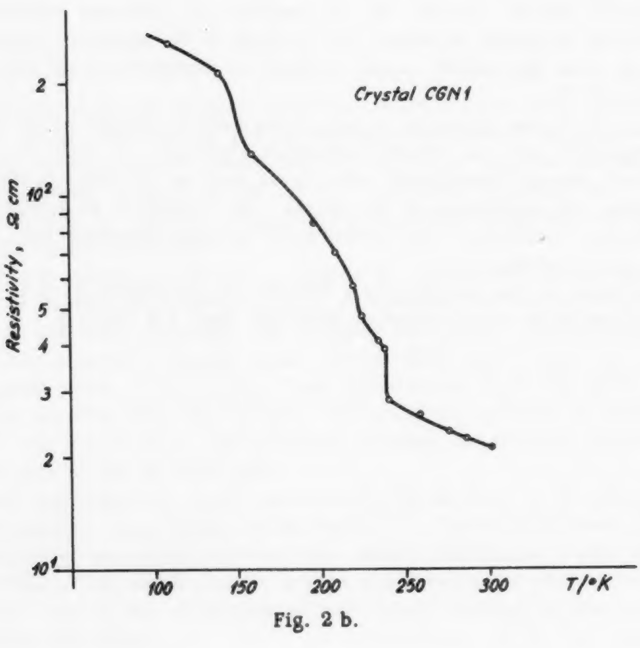
Crystal CGN1
Resistivity, Ω cm
2
10²
5
4
3
2
10¹
100
150
200
250
300
T/°K

Fig. 2 b.

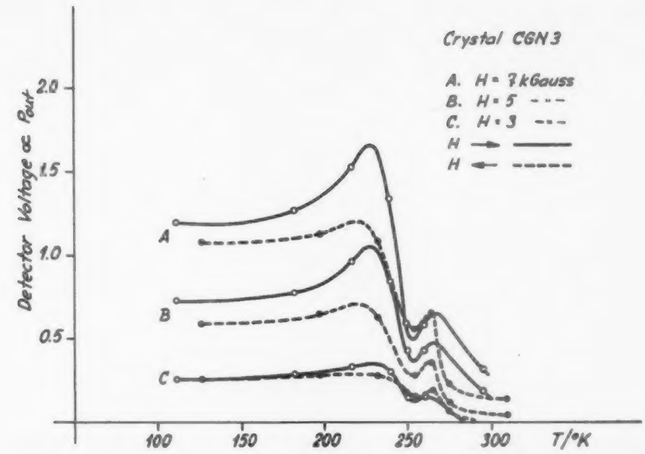
Crystal CGN 3
A. H = 7 kGauss
B. H = 5
C. H = 3
H
H
A
B
C
2.0
1.5
1.0
0.5
Detector Voltage ∝ P_{out}
100
150
200
250
300
T/°K

Fig. 3 a.

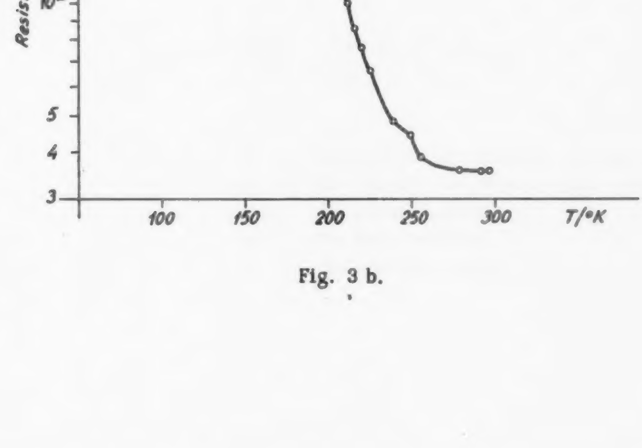
Crystal CGN 3
Resistivity, Ω cm
3
2
10^2
5
4
3
100
150
200
250
300
T/°K

Fig. 3 b.

FITTING OF CONTACTS AND ETCHING

In order to obtain a barrier-less layer in the D.C. measurements, various methods were tried. According to Schottky [13], an evaporated metal coating on a semiconductor provides barrier free contact. This is true if the electron release energy of the metal exceeds thet of the semiconductor. Contacts of this kind have been thoroughly investigated by Irmler [14]. In the present instance the following, method was used: The germanium surface was galvanically coated with Cu. The Cu atoms were then diffused into the germanium sample at 350^{o}C and the surface was ground with emery paper. An Au layer was evaporated onto this surface. This procedure produces a barrier-free layer for temperatures down to 100^{o}K, which is the lowest temperature employed in the present work.

A WAg solution was used for etching the samples, with +35^{o}C initial temperature of the bath. It is important to make sure that no Ag atoms remain on the surface after etching, as they might form a conductive layer and prevent the high-frequency power from penetrating the crystal.

THE HALL CONSTANT

In a region, in which the type of impurity mainly consists of electrons or holes, one may write for the Hall constant R_H:

$$R_H = - \frac{\mu_H}{\mu} \frac{I}{q\,n} \qquad (3)$$

where the negative sign refers to electrons and the positive sign to holes. The ratio of Hall mobility and drift mobility μ_H/μ, is dependen on the various scattering mechanisms and the shape of the energy surfaces. n stands for the number of carriers in the semiconduktor.

The scattering processes in the crystals in question are unknown and no study can therefore be made of the ratio μ_H/μ. Its value approaches unity for high magnetic field strengths and for degenerative semiconductors. If a model having spherical energy surfaces and Boltzmann's statistics are employed and if the assumption is made that the relaxation time is independent of energy, μ_H/μ can be assumed to have the value $3\pi/8$, as is well known.

In the case of samples in which electrons as well as holes contribute to the conductivity, one may write for R_H:

$$R_H = - \frac{3\pi}{8\,q} \frac{n\mu_n - p\mu_p{}^2}{(n\mu_n + p\mu_p)^2} \qquad (4)$$

where

n	the number of electrons per unit volume
p	the number of holes per unit volume
μn	the electron mobility
μp	the kole mobility
q	the electron charge.

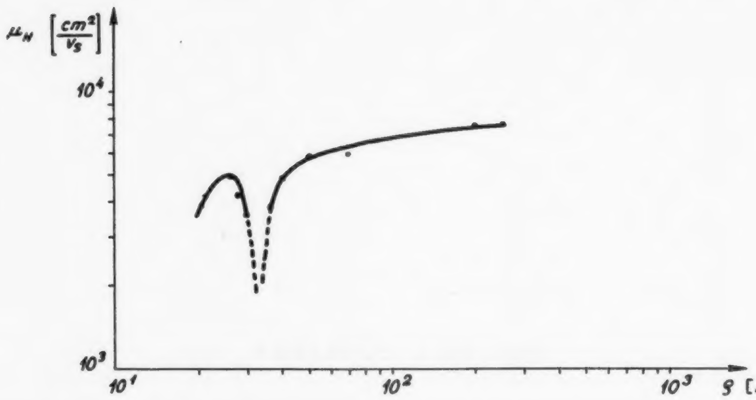

Fig. 4.

The formula (4) is only approximate and applies under the conditions stated for μ_H / μ , and for weak magnetic fields. A detailed study of R_H as a function of H has been made by Harman [15] and by Howord [16] .

It can be seen from the measured curve, Fig. 4. that temperature dependence of the Hall constant is insignificant at low temperatures. This is due to the fact that the impurities are still ionized and the ionization energy is low for donors as well as acceptors.

If $\mu_n / \mu_p < 1$, R_H is negative for all samples of n-type in the enitire temperature interval. For samples of p-type, R_H will change its sign when $n\mu_n^2 = p\mu_p^2$. The Hall constant has a maximum at a temperature slightly higher than that at which R_H changes its sign.

The n value for maximum R_H is [17]:

$$n = (N_A - N_D) / (\frac{\mu_H}{\mu} - 1) \qquad (5)$$

where

N_A the number of acceptor levels
N_D the number of donor levels.

The value of $R_{H_{max}}$ can therefore be calculated by the formula

$$R_{H_{max}} = \left[\frac{-3\pi}{8\,q(N_A\ N_D)} \right]^2 \frac{(b-1)^2}{4b} \qquad (6)$$

where b denotes the ratio μ_n / μ_p. In the exhaustic range, there is

$$R_{H_{ex}} = \frac{3\pi}{8q(N_A - N_D)} \tag{7}$$

Substitution of (6) and (7) yield the value of b, i.e.,

$$\frac{b^2 - 1}{4b} = -\frac{R_{H_{max}}}{R_{H_{ex}}} \tag{8}$$

DISCUSSION

In order to gain some kind of control of impurities occurring in the sample, R_H was plotted as a function of $1/T$; Fig. 5.

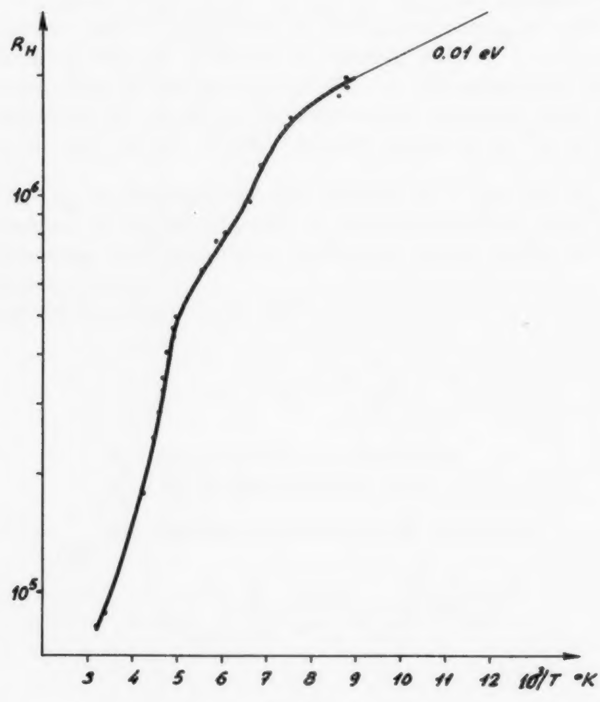

Fig. 5.

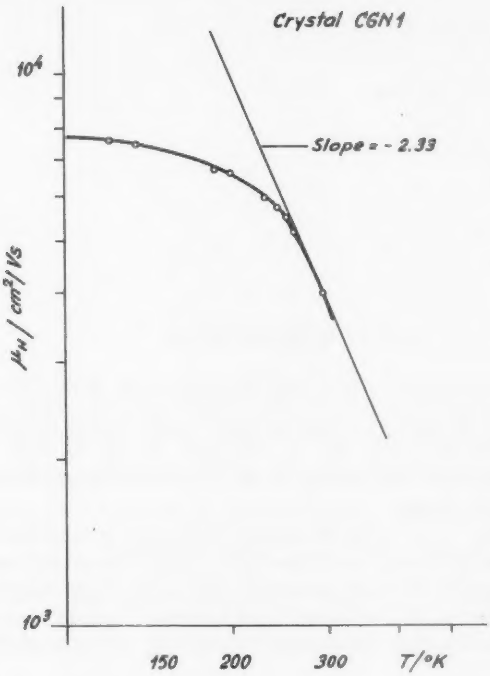

Fig. 6.

It can be seen that the ionization energy becomes 0,01 eV at low temperatures, which is the ionization energy for aluminium acceptors. Furthermore, Fig. 6, showing μ_H as a function of T, reveals that the mobility is proportional to $T^{-2,33}$, as has been previously demonstrated, e.g., by Morin & Maita[17].

The rapid change in resistivity at 240°K is hard to explain since the impurities in the crystal are unknown. Under any circumstanses, transition from one impurity, level to another must be concerned. It is likely that transition occurs from the aluminium level to a copper level.

The measuring methoa employed in this work is particularly reliable and has the great advantage over D.C. measurements that no contacts are required on the crystal. This advantage can be fully exploited at low temperatures and with high-ohm silica crystals.

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